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EFFECT OF BUBBLE INCLUSIONS ON THE MECHANICAL PROPERTIES OF CAST POLYMETHYL METHACRYLATE

by

J. D. Stachiw

Ocean Technology Department

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13 ABSTRACT

Bubbles are often present in acrylic plastic castings purchased from commercial sources. Since they may lower the strength of the finished product machined from such a casting, it is necessary to define quantitatively their effect on mechanical properties. The effect of bubbles on mechanical properties was evaluated by testing under uniaxial tension and compression 120 specimens machined from acrylic plastic castings. The tensile specimens failed at stress levels 7 to 30 percent lower than those observed in control specimens without bubbles. The stresses at which yielding under uniaxial compression took place were found to be the same as in the control specimens.

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SUMMARY

PROBLEM

Bubbles are often present in acrylic plastic castings purchased from commercial sources. Since they may lower the mechanical strength of the finished product machined from such a casting, it is necessary to define quantitatively their effect on mechanical properties.

RESULTS

The effect of bubbles on the mechanical properties of acrylic plastic was evaluated by testing of 120 specimens machined from castings with bubble inclusions. The specimens were tested under both uniaxial tension and compression.

The stress raiser effect of bubble inclusions caused the tensile specimens to fail at stress levels 7 to 30 percent lower than observed in control specimens without bubbles. The stresses at which yielding under uniaxial compression took place were found to be, however, the same as in control specimens without bubbles.

RECOMMENDATIONS

The allowable nominal tensile working stress in acrylic plastic with bubble inclusions should be 50 percent less than is generally allowed in acrylic plastic without bubbles.

The allowable nominal compressive working stress in acrylic plastic with bubble inclusions should be the same as in bubble-free acrylic plastic.

CONTENTS

INTRODUCTION

The successful launching and certification for manned dives of acrylic plastic submersibles – NEMO by the Naval Civil Engineering Laboratory, *Johnson-Sea-Link* by the Smithsonian Institution, and MAKAKAI by the Naval Undersea Research and Development Center – have proven that acrylic plastic is a reliable structural material for fabrication of submersible hulls. Its low cost and optical transparency make it ideal for pressure-resistant hulls on any manned submersible operating in the 0- to 3000-foot depth range.

Although the mechanical properties of acrylic plastic are well known and described by Federal and ASTM material specifications, very little is known about its structural behavior when bubbles are present in it. Such bubbles are usually generated during casting or subsequent curing. When they are observed, the question of their stress raiser effect invariably arises. If the magnitude of this effect were known, the reduced ability of plastic with bubble inclusions to withstand stresses would be taken into consideration and the depth rating of an acrylic pressure hull fabricated from such plastic reduced accordingly. The current alternative to this approach is to reject any acrylic casting in which bubbles are present. This makes the procurement of massive acrylic plastic castings for ocean engineering applications a very costly process.

To alleviate the lack of this kind of data, a low-effort study was undertaken at the Naval Undersea Research and Development Center. The objective of the study was to provide some quantitative data on the ability of acrylic plastic to carry tensile and compressive stresses in the presence of stress raisers in the form of bubble inclusions. The experimental study was conducted on compressive and tensile test specimens machined from massive acrylic castings with a large quantity of bubbles. Specimens without any bubbles served as test controls.

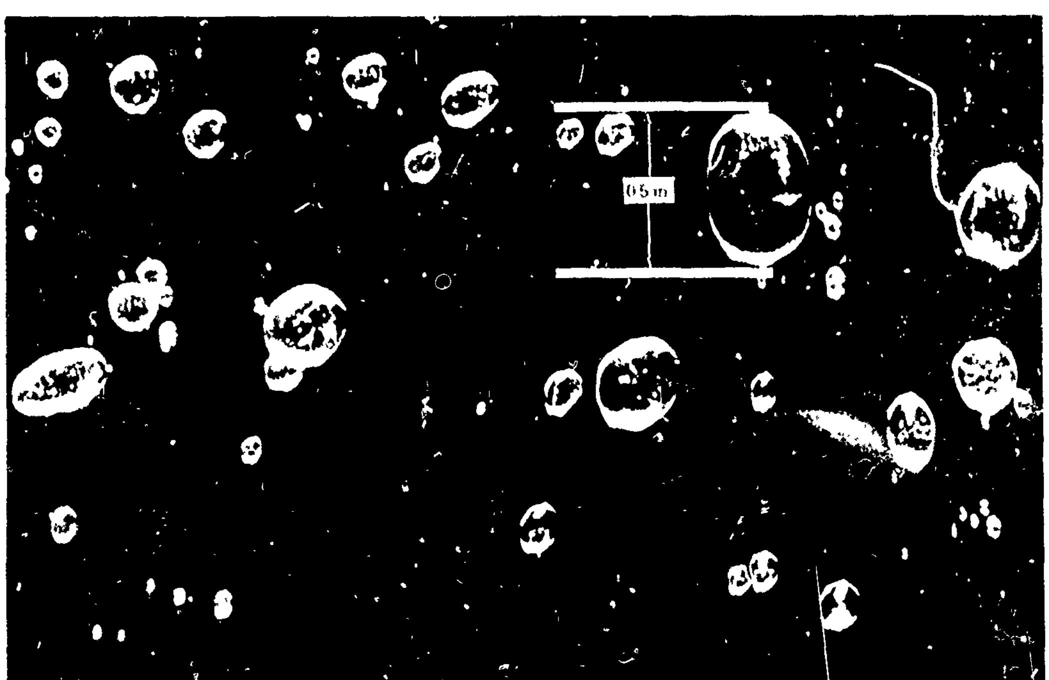
DISCUSSION

Bubbles can be found in almost any acrylic product when the process control has been less than perfect. Thus, one can find bubbles in cast sheets, massive custom castings, or cast joints in fabricated structures bonded together from many cast acrylic structural elements.

When bubbles are discovered in a piece of acrylic plastic, it is generally rejected because their presence is neither esthetically nor structurally beneficial. However, in cases involving large custom castings or complex fabricated structures, this either involves a severe economic penalty or makes the accomplishment of the technical objective impossible. Such is the case for (1) massive hemispherical castings used as pressure-resistant submersible windows and (2) cast-in-place joints bonding structural elements of acrylic pressure hulls for submersibles like NEMO, *Johnson-Sea-Link*, and MAKAKAI.

The presence of bubbles in the cast-in-place joints between individual spherical shell pentagons for NEMO-type modular hulls presented a difficult problem. (References 1- 5.) Regardless of what precautions and casting procedures were used, some bubbles were found to be present in the cast acrylic plastic joints (Figure 1). Rejection of all hulls with imperfect joints would in effect have cancelled the program for building of transparent plastic

a. Overall view of typical joint.



b. Enlargement of joint section.

Figure 1. Typical bubbles in cast PS-18 joints on NEMO-type acrylic plastic hull.

submersibles, for no NEMO-type hull built to date has been found to have completely bubble-free cast-in-place joints.

Thus, early in the NEMO hull construction program, it was decided to accept cast joints with bubbles, providing the bubbles were small and few in number. This decision was considered to be acceptable from the safety viewpoint because (1) the stress levels in the hull at maximum depth were only at 15 percent of yield strength and (2) the cyclic fatigue cracks always originated at the hatch-hull interface rather than at bubbles in the bonded joint.

This, however, still did not answer the question at which compressive or tensile stress loading the bubbles would act as initiators of cracks. Without this information the working stress could not be raised above the level equal to 15 percent of yield strength, and thus, by the same token, the capability of the acrylic hulls would be always limited to continental shelf depths.

It was hoped that, by performing an exploratory experimental study on this subject, sufficient information would be generated to give a quantitative value to the stress level at which cracks begin to radiate from bubbles. Knowing the stress level at which this occurs, the design engineer would be able to specify a working stress for the hull that maximized its operational depth without initiation of cracks.

EXPERIMENTAL PROCEDURES

The effect of bubbles on the mechanical strength of cast acrylic plastic was experimentally studied by uniaxially testing acrylic specimens machined from massive castings with bubble inclusions. Since the relationship between the size of the test specimen and the bubbles could be an additional variable amplifying the effect of bubble size on machined strength, several sizes of test specimens were utilized in the study. In this manner the effect of bubbles on the strength of small test specimens could be compared to the effect of bubbles on the strength of large specimens. If no difference between these effects was found, the size of test specimens would be considered insignificant. Specimens without bubbles served as controls. They were cut from the same massive castings as were the specimens with bubbles.

For uniaxial compression testing the specimens had a constant length-to-diameter ratio of two, and the diameters were 0.50, 1.00, 2.00, and 4.00 inches. Some test specimens contained bubbles that penetrated their surface, while in other cases all of the bubbles were located in the interior of the test specimen (Figure 2).

For uniaxial tension testing the specimens had the following dimensions: 0.25-inch outside diameter by 2.0-inch length, 0.500-inch outside diameter by 5.0-inch length, and 1.00-inch outside diameter by 5.0-inch length. The location of the bubbles varied (Figure 3) as in the compressive specimens: In some cases all were contained in the interior of the specimen, while in others they penetrated the exterior surface. Each specimen had adequate extensions on the ends to permit secure gripping in the test machine.

The tensile specimens were loaded at a rate of approximately 1000 to 2000 psi per minute till failure took place. Compressive specimens were loaded at approximately the same rate till yielding took place or cracks appeared at the bubbles.

Figure 2. Compressive specimens machined from massive acrylic plastic casting containing bubbles, 2.000 inches in diameter by 4.000 inches long.

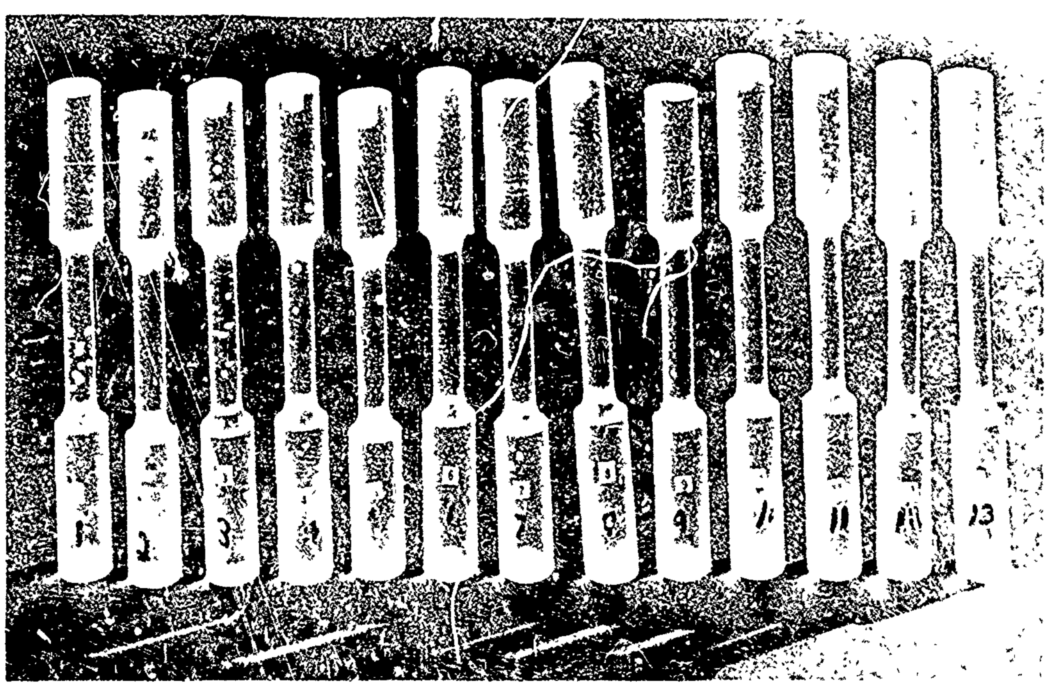


Figure 3. Tensile specimens machined from the same massive acrylic plastic casting, 0.500 inch in diameter by 5.000 inches long.

TEST OBSERVATIONS

TENSILE TESTS

Review of the experimental data indicates that the presence of bubbles decreased the tensile strength of acrylic plastic significantly. Furthermore, the decrease in strength was related to the number of bubbles in the test specimen. This can be readily seen by comparing average tensile strength values for test specimens categorized according to the number of bubbles they contained.

Number of Bubbles in Specimen	Average Tensile Strength
None	9154 psi
1	8515 psi
2	7695 psi
4-6	7453 psi
9-20	6420 psi

The location of bubbles (interior or exterior of specimen) appeared to have little influence on the stress level at which failure took place (Figure 4). Similarly no correlation was found between the size of the bubbles and the tensile strength so long as the bubbles ranged between 0.1 and 4.5 millimeters (0.004 and 0.18 inch). There appeared also to be no correlation between the tensile strength and the size of test specimen.

COMPRESSIVE TESTS

No significant correlation was found between the presence of bubbles and the compressive yield strength of acrylic plastic. The average strength was 10,072 psi for specimens without and 10,160 psi for specimens with bubbles. Thus it appears that bubbles have no effect on compressive yield strength, providing their total volume is less than 1 percent of the test specimen volume.

Although bubbles appeared to have no effect on the yield strength of the acrylic plastic (in less than 1 percent by volume concentration), they served as crack initiators when the uniaxial compression strain was in excess of 5 percent. The fracture planes always were oriented in the direction of the applied load and originated at the poles of bubbles in line with the load application axis (Figure 5). If the test specimens were compressed in excess of 10 percent, visually noticeable distortion of the bubbles took place. The originally spherical bubbles were transformed into slightly squashed spheroids (Figure 6).

The compressive strength of the massive castings from which the tensile and compressive test specimens were machined was somewhat less than for the Plexiglas G acrylic plastic sheets used for the fabrication of NEMO hulls (10,000 vs. 15,000 psi). If submersible hulls were to be machined from massive acrylic castings with lesser mechanical properties than Plexiglas G, the operational depth of such hulls would have to be reduced accordingly. The reasons the massive castings had a reduced compressive yield strength are not known.

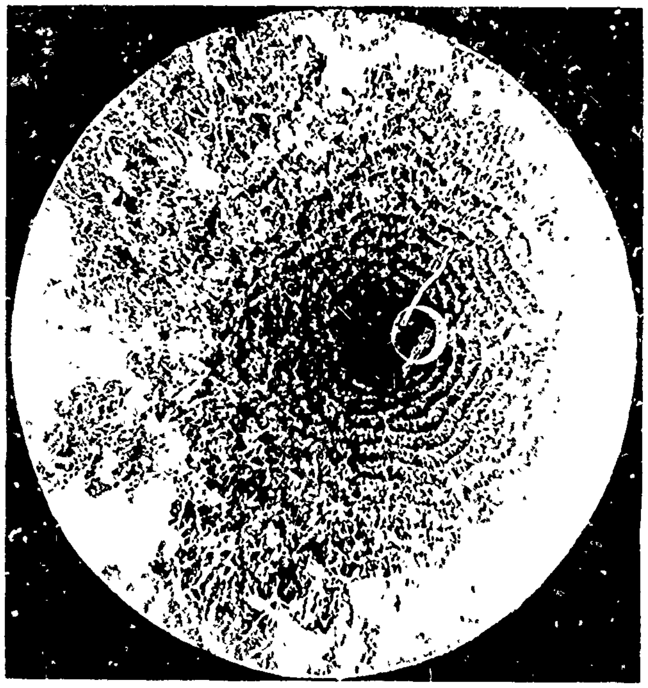


Figure 4. Typical fracture initiated by bubble in specimen under uniaxial tensile loading; test specimen diameter, 0.500 inch.

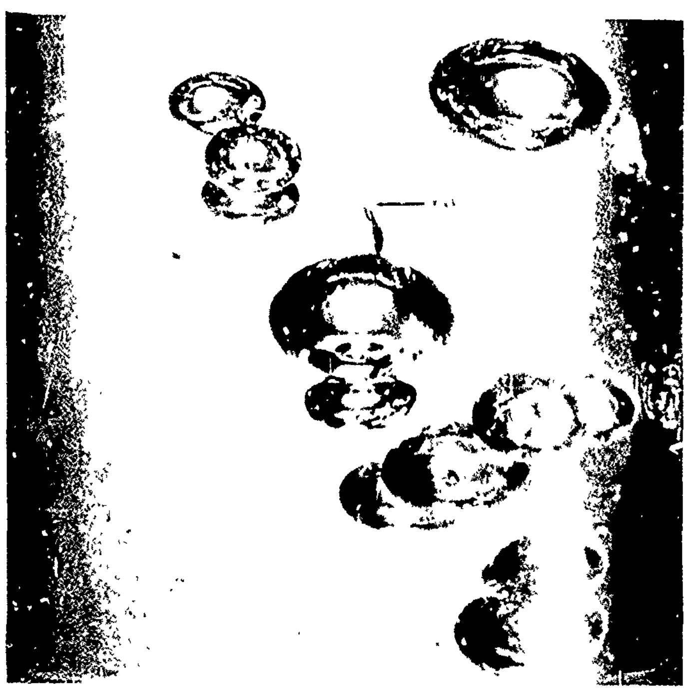


Figure 5. Typical fracture initiated by bubble in specimen under uniaxial compressive loading; the 0.200-inch-diameter bubble is located in a 2.000-inch-diameter specimen.

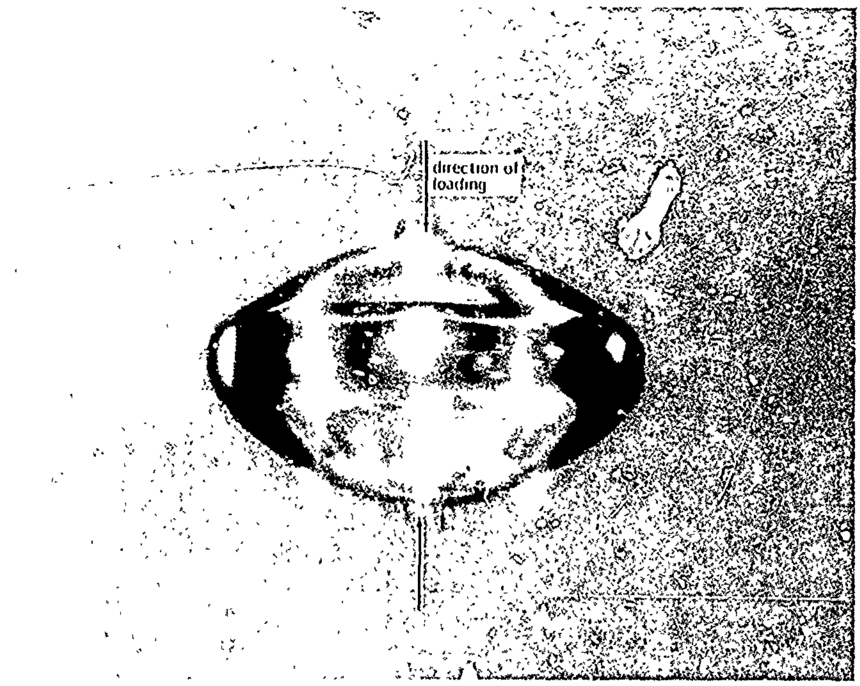


Figure 6. Typical spherical bubble in a specimen that has been subjected to approximately 10-percent uniaxial compressive strain; the 0.100-inch-diameter bubble is located in a 2.000-inch-diameter specimen.

CONCLUSIONS

The presence of bubbles in a massive acrylic plastic casting reduces significantly the ability of parts machined from the casting to carry tensile stresses. As a result the nominal working tensile stress of such parts should be lower than when a casting without bubbles is used.

Bubble inclusions do not affect the nominal compressive yield strength of acrylic plastic. However, they act as fracture sources when the plastic is uniaxially compressed more than 5 percent. Thus the magnitude of the nominal working compressive stress in castings with bubbles can be the same as in castings without bubbles. The magnitude of the peak working stress around stress raisers must be, however, lower than for bubble-free castings.

Table 1. Ultimate Tensile Strength of Specimens Machined from Massive Acrylic Plastic Castings.

Specimen	Diameter (in.)	Total Number of Bubbles	Number of Bubbles in Fracture Plane	Size of Bubbles in Fracture Plane (mm)	Initiation of Failure*	Ultimate Stress (psi)
1	0.25	1	1 inside	0.1 or less	Bubble in center	10200
2	0.25	1	1 at edge	0.1 or less	Bubble at edge	9200
3	0.25	0	None	–	At edge	10400
4	0.25	0	None	–	At edge	10000
5	0.25	0	None	–	At edge	9200
6	0.25	0	None	–	At edge	10000
7	0.25	0	None	–	At edge	9200
8	0.50	14	1 inside, 1 at edge	1.2; 3.2	L bubble at edge	5310
9	0.50	4	1 inside, 1 at edge	2.7; 1.8	L bubble at edge	6800
10	0.50	8	2 inside	1.6; 1.0	2 bubbles at edge	6820
11	0.50	2	1 inside	3.2	L bubble inside	6550
12	0.50	4	1 at edge	2.2	S bubble at edge	6300
13	0.50	1	1 inside	2.4	Bubble at edge	6300
14	0.50	1	1 inside	1.8	Bubble at edge	6350
15	0.50	0	None	–	At edge	7850
16	0.50	0	None	–	At edge	8250
17	0.50	0	None	–	At edge	8200
18	0.50	0	None	–	At edge	8210
19	0.50	0	None	–	In center	11000
20	0.50	1	1 inside	0.1	Bubble center	9200
21	0.50	1	None	–	At edge	8750
22	0.50	4	2 inside	2; 1.5	2 M bubbles at edge	7100
23	0.50	0	None	–	At edge	10250
24	0.50	5	1 inside	1.0	S bubble 1/4 way in	7620
25	0.50	2	None	–	At edge	7770
26	0.50	1	1 inside	0.4	At edge	7500
27	0.50	1	1 inside	1.0	Bubble at edge	7750
28	0.50	0	None	–	At edge	8200
29	0.50	1	1 inside	1.6	Bubble 2/3 way in	7670
30	0.50	4	1 inside	3.1	Bubble at edge	6950
31	0.50	0	None	–	At edge	8900
32	0.50	0	None	–	At edge	8500
33	1.00	13	1 inside	1.8	Bubble at center	7050
34	1.00	2	2 inside	3; 3.1	Bubble at edge	7850
35	1.00	14	1 inside	6.1	Bubble at edge	6050
36	1.00	10	1 inside	3.9	Bubble at edge	5850
37	1.00	5	1 inside	2.9	Bubble at edge	7700
38	1.00	2	1 inside	2.0	Bubble 1/4 way in	8050
39	1.00	0	1 inside	1.4	At edge	10200
40	1.00	20	1 inside	2.2	Bubble at center	7450
41	1.00	5	1 inside	2.6	Bubble 1/4 way in	8200
42	1.00	10	2 inside	1.0; 0.8	2 bubbles at center	6100
43	1.00	10	2 inside	3.5; 2.8	L bubbles at edge	6750
44	1.00	9	1 inside	2.0	Bubble at edge	6740
45	1.00	3	2 inside	3.8; 2.5	Bubble 1/4 way in	7250
46	1.00	6	2 at edge	4.5; 4.5	Bubble at edge	7300
47	1.00	5	1 inside	1.6	Bubble at edge	7500
48	1.00	3	1 inside	0.6	Bubble 2/3 way in	7300
49	1.00	4	1 at edge	0.1; 0.2	Bubble at edge	7500
50	1.00	2	2 inside	2.8; 1.7	At edge	8410

*T = tiny (approx. 0.1 mm); S = small (approx. 1.5-2.5 mm); M = medium (approx. 3 mm); L = large (approx. 4-5 mm).

Table 2. Compressive Yield Strength of Specimens Machined from Massive Acrylic Plastic Castings.

Specimen	Diameter (in.)	Total Number of Bubbles	Size of Bubbles*	Yield Strength (psi)
1	0.500	6	LM	8900
2	0.500	6	LM	10350
3	0.500	2	L	8600
4	0.500	1	L	8900
5	0.500	4	SM	8800
6	0.500	0	–	9950
7	0.500	0	–	10100
8	0.500	0	–	11700
9	0.500	0	–	9850
10	0.500	0	–	10100
11	0.500	1	T	9670
12	0.500	0	–	10500
13	0.500	0	–	10500
14	0.500	1	M	8900
15	0.500	0	–	10200
16	0.500	0	–	9650
17	0.500	0	–	10300
18	0.500	0	–	10200
19	1.000	0	–	10200
20	1.000	0	–	10000
21	1.000	0	–	10700
22	1.000	0	–	10950
23	1.000	0	–	9450
24	1.000	0	–	10100
25	1.000	0	–	11000
26	1.000	0	–	9700
27	1.000	0	–	10200
28	1.000	0	–	9050
29	1.000	7	M	10700
30	1.000	9	M	10850
31	1.000	11	LM	10450
32	1.000	9	SML	11450
33	1.000	10	SML	10300
34	1.000	6	LM	10250
35	1.000	10	SML	10100
36	1.000	13	ML	9650
37	1.000	7	SM	10800
38	1.000	7	ML	10100
39	1.000	41	LS	9500
40	1.000	12	LS	9600
41	1.000	12	LS	9700
42	1.000	10	LS	10150
43	1.000	12	S	10200
44	1.000	6	M	10800
45	1.000	10	LS	9700
46	1.000	6	S	10600
47	1.000	8	M	10500
48	1.000	6	M	10200
49	1.000	2	S	10700
50	1.000	13	M	9700
51	1.000	0	–	10100
52	1.000	23	M	10700
53	1.000	30	ML	9250
54	1.000	18	M	9800
55	1.000	23	M	11450
56	1.000	–	–	–
57	1.000	7	M	10200
58	1.000	6	ML	9700
59	1.000	4	T	10600
60	1.000	1	S	10500
61	2.000	34	ML	10800
62	2.000	6	ML	10800
63	2.000	3	T	12100
64	2.000	0	–	10200
65	2.000	5	T	11500
66	2.000	0	–	12400
67	2.000	0	–	12800
68	2.000	30	TSM	9500
69	4.000	105	ML	10300
7	4.000	55	ML	9800

*T = tiny (approx. 0.1 mm); S = small (approx. 1.5-2.5 mm); M = medium (approx. 3 mm); L = large (approx. 4-5 mm).

RECOMMENDATIONS

In structures fabricated from acrylic plastic castings the *allowable nominal working tensile stress* should be 50 percent less when bubbles are present than when they are absent. (In bubble-free castings, the maximum allowable working tensile stress is 1500 psi. The 6-to-1 ratio between the 9000-psi short-term tensile strength of acrylic plastic and 1500-psi working stress takes into account the effects of static and cyclic fatigue, which will cause an acrylic casting to fail in service at a stress level below 9000 psi.)

The *allowable nominal working compressive stress* in an acrylic plastic casting with bubble inclusions should be the same as in bubble-free castings, except that local peak compressive strains should not exceed 3 percent. (In bubble-free acrylic plastic castings the allowable nominal working compressive stress is 5000 psi, providing local peak compressive strains at structural discontinuities do not exceed 6 percent.)

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